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COMBINED REFRIGERANT VOLUME CONTROL THROUGH AN ELECTRONIC EXPANSION VALVE WITH THE SELF-TUNING FUZZY ALGORITHM APPLIED

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ABSTRACT

This paper gives a study of how to carry out a combined refrigerant volume control using an electronic expansion valve (EEV) and the specific measures to apply self- tuning fuzzy algorithm to refrigeration control system. The simulation analysis on the superheat fuzzy controller was completed by Simulink. Different scale factors and weight factors were employed during the process, and their effects on the controller were concluded, Based the self-tuning fuzzy controller was developed by changing these factors on line through some algorithms. The combined refrigerant volume control method through the EEV was proposed, and its validation was verified by experiments. Keywords: Electronic expansion valve, Refrigeration, Self- tuning fuzzy control, Scale factor

INTRODUCTION

With the stricter requirements on comfort and energy consumption, great innovation in refrigerating control system has been taking place, which is characterized by updated control methodologies and new- style automatic control apparatus[1]. Taking advantage of the electronic expansion valve (EEV) and the inverter- driven compressor[2], nowadays the artificial intelligent control method applied to refrigeration system is becoming the focused research areas. However, in spite of the broad application of the compressor capacity adjustment in HVAC equipment[3], lots of vapor compression machines still belong to the constant speed system that is controlled mainly through the EEV. Many former related literatures are aimed at regulating one variable throughout the whole running process and lots of valuable conclusions have been derived[4~6]. Nevertheless, such control method as only one parameter modulated is necessary but not sufficient to remarkably improve system performance and energy efficiency. Developing combined control methodology (superheat, evaporation pressure and discharged gas temperature concerned here) by changing EEV opening, the topic of this paper, thus becomes important for constant speed machines.

Because of its non- liner, long delay and coupling characters, refrigeration system has poor performance by traditional controllers such as On-Off or PID in terms of transient and steady behavior, which is also true even for non- adaptive fuzzy controllers. Lately all sorts of improved fuzzy controllers were developed in an attempt to achieve better qualities[7,8]. As a flexible and adaptive control algorithm, self- tuning fuzzy control has shown great advantage in thermodynamic system modulation and its application in this area was further studied in this paper. Taking the superheat fuzzy controller as an example, the simulation analysis was firstly completed to explore the effects of scale factors and the weight factor on system performance, which provided the foundation for designing the self- tuning fuzzy algorithm. Based on the identified transfer function model for evaporator, the simulation model of superheat fuzzy control system was established with Simulink[9].

SIMULATION ANALYSIS ON THE SUPERHEAT FUZZY CONTROL SYSTEM

Superheat fuzzy controller

As a two dimensional SISO (Single- Input Single- Output) control loop, the superheat fuzzy controller has two inputs and one output, shown as Fig. 1.

Two inputs include the superheat error *e* ranging form -10℃ to 10℃ and its derivative on time *ec* from –0.1 ℃/s to 0.1℃/s; the output is the EEV pulse number increment *u*, whose range is limited between –40 and 40 to avoid sharp fluctuate of the EEV opening and therefore the superheat. All the domains for the three variables above are defined as {-4,-3,-2,-1,0,1,2,3,4}. To map the actual input *e* and *ec* to their corresponding domains, the **input**

scale factors k_1 and k_2 are respectively used which are determined as follows.

$$k_1 = \frac{4}{10} = 0.4 \quad (1)$$

$$k_2 = \frac{4}{0.1} = 40 \quad (2)$$

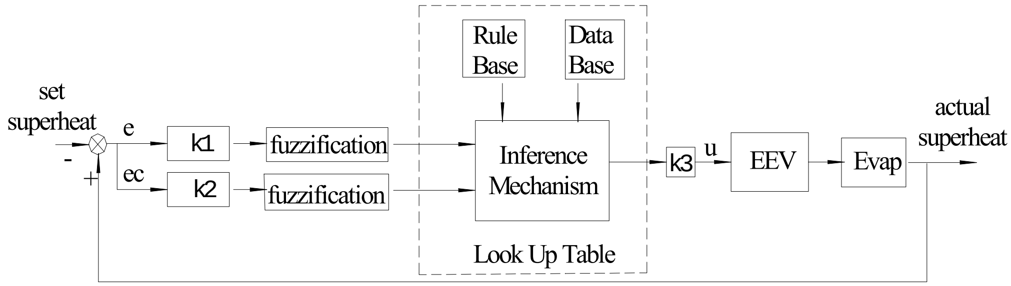


Fig. 1 Superheat Fuzzy Controller

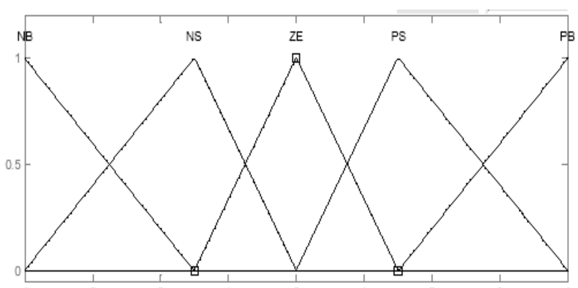
After mapped into the domains the inputs are fuzzificated as Fuzzy Singleton. According to the information provided by database and rule base, the *Mamdani* inference mechanism is activated to obtain the fuzzy output which is then defuzzificated into one point in the output domain by the *centroid* defuzzification method. The **output scale factor k_3** is used then to calculate the precise output of pulse number increment to regulate the EEV and the superheat accordingly. k_3 is computed using the following formula

$$k_3 = \frac{40}{4} = 10 \quad (3)$$

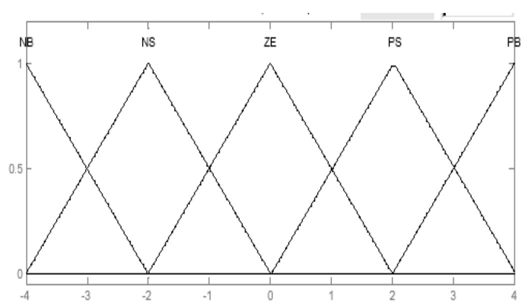
What is stored in database comprises the definition of domains for both inputs and outputs and all fuzzy sets. Three capital letters *E, EC* and *U* each denote one fuzzy variable, e.g. the superheat error, its derivative on time and the pulse number increment, all of which are described by five fuzzy sets represented by lingual terms as follows:

$$\{NB, NS, ZE, PS, PB\}$$

The triangle membership functions used to determine to what extent a particular value belong to a fuzzy set, shown as Fig. 2, are adopted for all the three fuzzy variables, among which the superheat *E* and its derivative *EC* share the same five triangle functions.



(a)



(b)

Fig. 2 (a) Membership functions for *E* and *EC* (b) Membership functions for *U*

A set of rules in linguistic terms are stored in rule base to describe relationships between input and output, which are induced from experts' experience firstly and then used to specify the control action during the fuzzy inference process. For superheat control system, all the 25 rules are listed in table 1.

Table 1 Superheat fuzzy control rules

EC \ *E* / *U*	NB	NS	ZE	PS	PB
NB	NB	NB	NS	ZE	PS
NS	NB	NS	NS	ZE	PS
ZE	NB	NS	ZE	PS	PB
PS	NS	ZE	PS	PS	PB
PB	NS	ZE	PS	PB	PB

Simulation model for superheat fuzzy control system

The simulation model constructed by *Simulink* is depicted in Fig. 3.

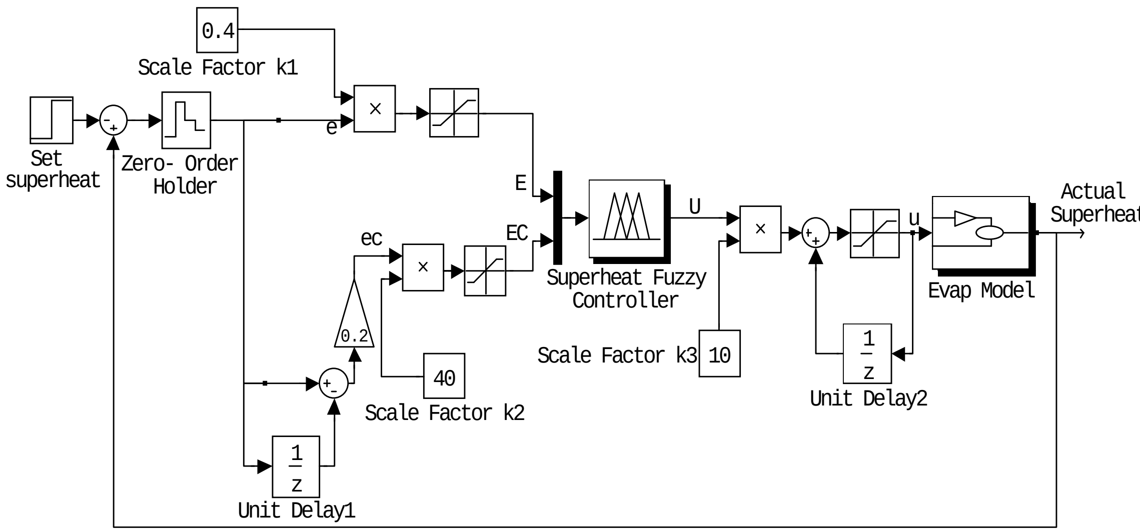


Fig. 3 Simulation Model for Superheat Fuzzy System

The superheat fuzzy controller in this figure is established by the Fuzzy Inference System (*FIS*) toolbox of *Matlab*. Through workspace the controller configuration matrix is linked to the simulation model to perform control actions. Consisting of both continuous and discrete blocks, this simulation model belongs to the combined simulation model for continuous system. The discrete blocks mainly include the zero- order holder and the unit delay, which are employed not only to determine the superheat derivative on time and the EEV positional pulse number, but to keep the EEV remain its opening for tens of seconds to fully stimulate the evaporator- the continuous block in the model. The mapping for inputs and outputs are completed by three multipliers. Three saturation blocks are used to limit the mapped values between the bounds of their relevant domains. All the simulation results are stored in the workspace to make the analysis convenient. Fig.4 pictures the first-order transfer function model with delay for EEV-Evap subsystem obtained by classical identification

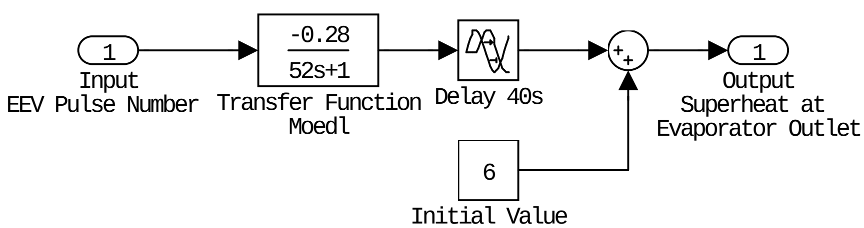


Fig. 4 EEV-Evap subsystem model

Simulation process

The five-order *Runge-Kutta* numerical integral algorithm with variable paces is employed to simulate the system following the procedures below.

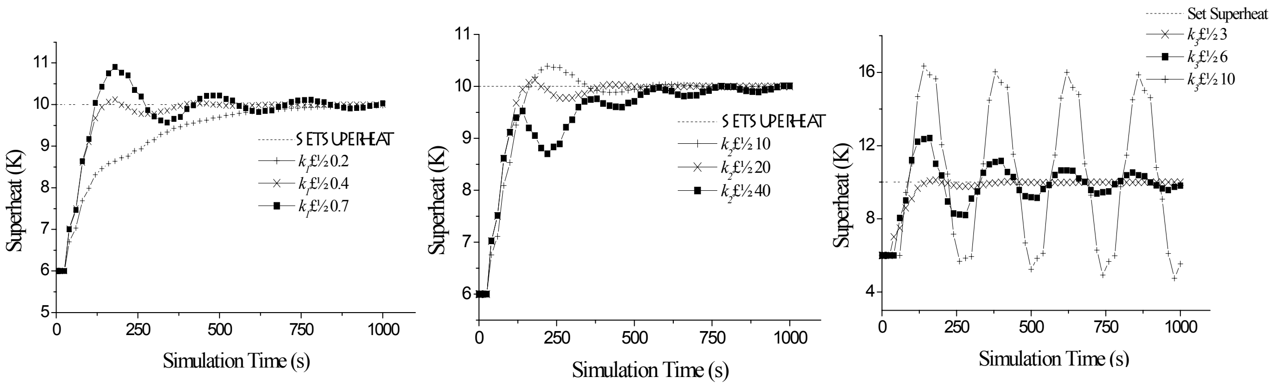
1） Scale factors

The typical single variable two dimensional fuzzy controller can be described approximately as

$$u = k_3 f(k_1 e, k_2 ec) \tag{4}$$

where f is a nonlinear function[10]. It is evident that the *FLC* output u depends largely on the scale factors k_1, k_2, k_3 when the membership functions and the rules of the controller are fixed. The alternation of these three parameters will respectively modify the proportional and derivative effects on the inputs and the amplifier of the defuzzifier output, resulting in great changes of the fuzzy controller performance. After the set superheat stepped from 6℃ to

10℃ at the instant of time "0", the simulation analysis began with different scale factors and some final results were shown in Fig. 5. At this stage the weight factor were not used.



(a)k_2=20; k_3=3 (b) k_1=0.4; k_3=3 (c) k_1=0.4; k_2=20

Fig. 5 Superheat control system response to step input

2） Weight factor

For a two dimensional fuzzy controller, its look- up table can be described approximately by formula (5) when the fuzzy input variables *E*, *EC* and output *U* have the same domains.

$$U \approx (E + EC)/2 \tag{5}$$

It demonstrates that the fuzzy output variable *U* is completely determined by *E* and *EC*, whose weights are both 0.5 and cannot be changed. Based on this formula an adjustable weight factor α is introduced to alter the importance of the inputs *E* and *EC* on the output *U*, and as a result, the set of control rules are also modified[11].

$$U = [\alpha E + (1-\alpha)EC], \alpha \in (0,1) \tag{6}$$

To analyze the weight factor's effects on the control system a S-*function* block is inserted into the before-mentioned simulation model, whose job is to increase the weight of the superheat error *E* if it is too much and contrarily the weight of *EC* is increased. Under the same condition, the simulation was performed with the weight factor and the results are shown in Fig. 6.

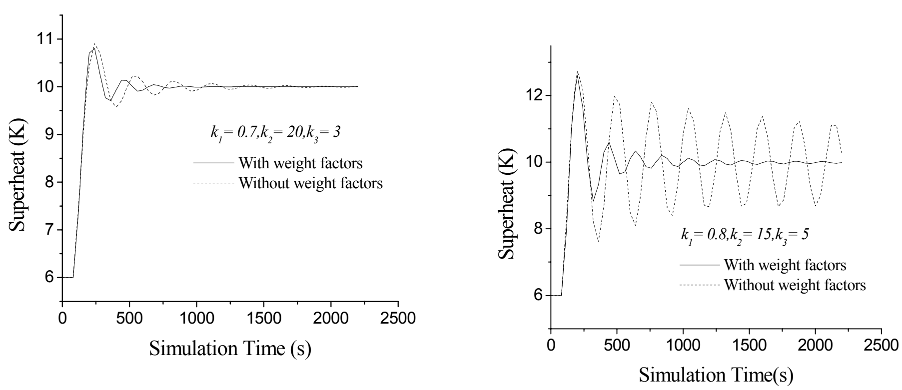


Fig. 6 Superheat control system response to step input with weight factor

Results analysis

1） The dead zone and the adjustment inertia will lesson when k_1 increases, and simultaneously the ascending speed will become faster. But oversized k_1 will cause the overshoot to increase largely and the system oscillation become evident. On the contrary the adjustment inertia will increase if k_1 is too little which will also influence the system steady properties.

2） The big k_2 can not only effectively restrain the change of the system state, but keep the system relatively stable. The transient time will lengthen if k_2 is too big and the ascending speed will increase if k_2 become very small, which will result in severe overshoot as well as oscillation and divergence.

3） With k_3 increasing the total amplitude of the system augments and the response speeds up. The oversized k_3 will lead to oscillation and maybe divergence. On the other hand the ascending speed will decrease and the system become inert.

As shown in Fig. 6, after the weight factor is employed the system can quickly approach to stability with small overshoots and short oscillation periods. The control performance is much more satisfactory than those cases without the weight factor

All the conclusions above shows that both the scale factors and the weight factor have significant influence on the system transient and steady properties. To achieve optimal control it is necessary to alter these parameters on line according to the current system state, e.g. to carry out self- tuning fuzzy control.

SELF- TUNING FUZZY CONTROLLER

1） Scale factors self- tuning controller

Scale factors self- tuning controller is shown in Fig. 7. Compared with the conventional *FLC*, the scale factors self-tuning *FLC* has two additional function modules. One is the system property test module through which a set of criterions describing the current system state are calculated. According to these data another module is used to alter the scale factors on- line by some modification algorithm.

Including overshoot, oscillation degree, transient time and steady error, all the criterions are defined by a group of fuzzy linguistic variables denoted by *OVS, VM, STIME* and *EAC* respectively. Based on former conclusions, the scale factors can be altered as following ways after one of them, usually k_1, is fixed firstly by expert experience,

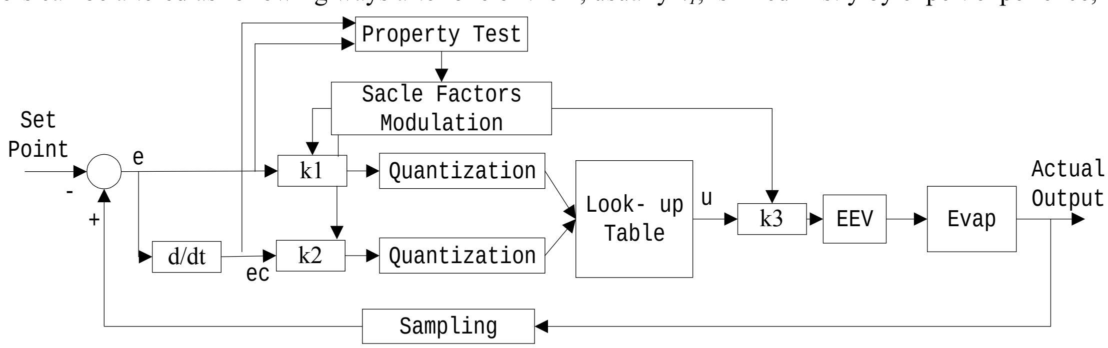


Fig. 7 Scale factors self- tuning fuzzy controller

(1) Moderately increase k_3 and simultaneously increase k_2 just a little according to system static errors if they exist.
(2) Decrease k_2 slightly according to the transient time if it is too long.
(3) Increase k_2 moderately according to the overshoot if it is too big.
(4) Decrease k_3 according to the system oscillation and divergence situation if they emerge.

k_1 is fixed at 0.7 for superheat fuzzy controller and 150 for evaporation pressure fuzzy controller from experimental results. The specific algorithm modifying k_2 and k_3 is expressed in formula (7)~(8),

$$k_3 = k_3'[1 - VM \times 0.4 + (1 - EAC) \times 0.4] \tag{7}$$

$$k_2 = k_2'[1 - (1 - STIME) \times 0.2 + (1 - OVS) \times 0.4 + (1 - EAC) \times 0.2] \tag{8}$$

where k_3' and k_2' represent the previous modification results. Every five minutes, more or less, the scale factors are modulated in terms of the methods above.

2） Weight factor

On the basis of simulation outcomes the author developed a brand- new way to modulate the weight factor. Firstly the sampled error *e* is fuzzificated to obtain the original fuzzy variable *E*, which is employed to choose the current weight factor α_i . The error *e* and its derivative on time *ec* are then fuzzificated again taking account of the weight factor as the equations below,

$$\begin{cases} E' = FUZZY[\alpha_i e], \\ EC' = FUZZY[(2 - \alpha_i) ec], \end{cases} i = 1 \sim 9 \tag{9}$$

where *E’* and *EC’* are the fuzzy input variables obtained the second time. When *E* takes its value from –4 to 4, the corresponding weight factor ranges from α_1 to α_9 in a sequence. In accordance with the rules that the weight factor for *e* should be a little bigger when the error is evident and that for ec should be a little bigger if the error is neglectable, and simultaneously considering the phenomenon observed in experiments that the system reacts sluggishly to the change of EEV opening when the error is negative, all the weight factors must satisfy the following relationship.

$$0 < \alpha_5 \le \alpha_6 < \alpha_4 \le 1 \le \alpha_7 < \alpha_3 < \alpha_8 < \alpha_2 < \alpha_9 < \alpha_1 < 2 \qquad (10)$$

The rectified control output *u* can be determined through the look- up table by E' and EC'. In the rest research these two kinds of self- tuning methods mentioned above are both applied.

COMBINED REFRIGERANT VOLUME CONTROL

The principle of the vapor compression refrigeration cycle tells us that the increment of the EEV opening will expand the refrigerant volume feeding the evaporator, causing the superheat and the discharged gas temperature to fall down while the evaporation pressure to increase, and vice versa. Therefore the change of the refrigerant volume will remarkably influence the superheat as well as the discharged gas temperature and the evaporation pressure. This phenomenon did inspire the author to propose the combined refrigerant volume control method through only one actuator, the EEV. The basic idea is to choose the different variables as present control target by estimating the current system state and control it to quickly approach the set-point by regulating the EEV opening.

The control flow chart designed for the cold storage is shown in Fig. 8, which works as follows. During the period from the machine starting until the in-house temperature T_{in} approaching its set point $T_{inset,}$ the superheat T_{sh} is the target variable in order to make full use of the evaporator heat transfer areas, shorten the cooling time and reduce the system energy consumption. Although the evaporation temperature (or pressure P_{evap}) is relatively high at this stage, T_{in} is also comparatively high keeping the transfer temperature difference nearly unchanged and therefore the transfer efficiency. After T_{in} approaches T_{inset} the cold storage enters the steady operation phase when it is necessary to maintain P_{evap}, which becomes the current target variable thereby. During the later process if the in- house temperature and the superheat ascend evidently due to the abrupt load increment, T_{sh} becomes the target again until T_{in} return to set-point, and then P_{evap} is controlled. During the course of steady operation, the refrigerant volume should be increased to regulate P_{evap} if it is below the set-point, but unfortunately this act may cause T_{sh} to fall down even to zero. This problem is solved by installing a gas-liquid separator on the suction line. Not only is the hunting avoided, but also P_{evap} won't drop

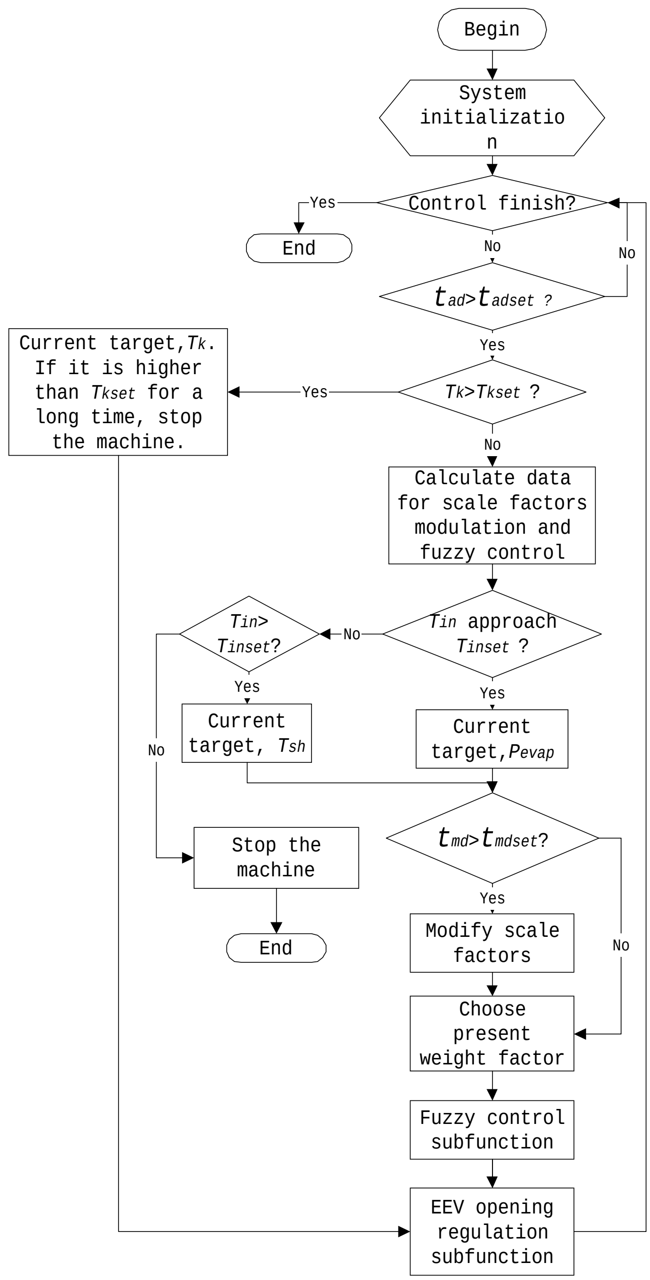


Fig. 8 Combined refrigerant volume control flow chart

quickly duo to the decrement of refrigerant volume in an attempt to regulate T_{sh}. The discharged gas temperature T_k is monitored throughout the running and chosen as the current target variable once it is higher than the maximum value permitted to ensure the system safety. Other than T_k modulated by *P(Proportional)* controller, the other two T_{sh} and P_{evap} are both regulated by self- tuning fuzzy controller. To verify the feasibility of this method, a series of experiments were performed on the cold storage, one of which was completed under the conditions stated in the next paragraph and its results are shown in Fig.9.

Set-points: T_{shset}=8℃, $P_{evapset}$=0.164*Mpa*, T_{inset}=-10℃; EEV opening adjustment intervals: T_{ad}=55s/35s; Scales factors: k_1=0.7/150, k_2 and k_3 are tuned on- line. The weight factor is only used in superheat fuzzy controller. At the time of 1870s the electric heater inside the storage is turned on to 1500*W*, and is shut off at 2000s. The figure at the left of the slash "/ " in the former expressions represents the value for the superheat control while the right for the evaporation pressure control.

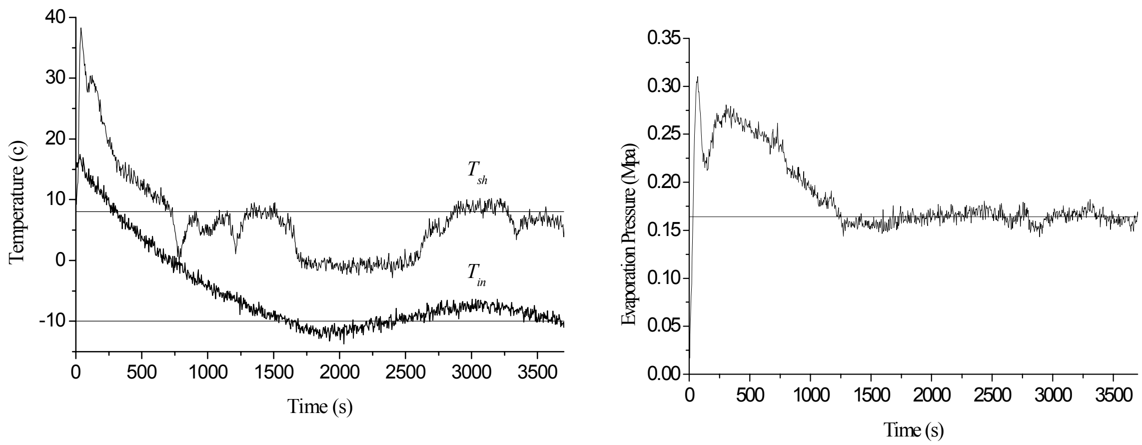


Fig. 9 Combined refrigerant volume control experimental results

The results show that P_{evap} was well controlled in spite of no weight factor used. Since 1200s it had remained around the set- point 0.164*Mpa*. However, as the target the superheat T_{sh} still dropped quickly to zero when T_{in} descended to 0℃ at 750s (This phenomenon was observed in all experiments. The author's explanation will be given later), but under the control it returned to the set- point after a short while. The controlled variable switched to P_{evap} when the storage was cooled to -10℃. Since then T_{sh} decreased gradually to zero as predicted theoretically. After the electronic heater was turned on the in- house temperature began to regress. When it returned to -8℃ T_{sh} became the controlled variable and hereafter kept its value around 8℃. Fifteen minutes later the electrical heater was shut off and the in- house temperature fell down. The controlled variable did not switch to P_{evap} again until T_{in} arrived at -10℃.

The whole operation process coincided with the designed requirement to regulate the superheat as well as the evaporation pressure and the discharged gas temperature only through the EEV, with the control qualities better than conventional controllers.

EXPLANATION ON UNEXPECTED EXPERIMENT PHENOMENON

An unexpected and interesting phenomenon was noted during the experiments. Almost in all cases instead of remaining stable the superheat dropped quickly to zero after it approached the set-point the first time. Suppose that it was led by the random error was rejected because of its universality. Through careful analysis a possible explanation was given by the author. In this experiment the cold storage was cooled far below the freezing point 0℃, which caused frosting on the surface of the evaporator become very serious. With the accumulation of the frost the heat transfer resistance increased while the circulation areas between the fins decreased, leading to the air flow rate passing the evaporator decrease too. All these factors together with the lessening of the temperature difference forced the heat transferred to reduce gradually. Some time later the heat transfer efficiency and the conditions deteriorated suddenly which led to the severe deficiency of the heat transferred through the evaporator and the rapid decline of the refrigerant temperature at the evaporator outlet. Therefore the refrigerant superheat decreased remarkably because the inlet temperature maintained nearly unchanged. Not until did the refrigerant volume feeding the evaporator reduce largely the superheat began to change reversedly. At that time the superheat became sensitive even to small increment of the refrigerant volume but relatively dull to its decrement. Hence when developing the controller for the evaporator used to cool the air some specific algorithms should be designed to force the superheat to increase as quickly as possibly after it approaches 0℃.

CONCLUSION

This paper firstly presented the simulation study on the superheat fuzzy control system, based on which the effects of the scale factors and the weight factor on the fuzzy control system was concluded. The self- tuning fuzzy controller was developed later including two kinds of adjustable factors. One was the scale factors altered on line in terms of a set of system state criterions of the time, and another was the weight factor determined by the fuzzificated error *E*, employing which two inputs were fuzzificated again to obtain the rectified output. After that the combined refrigerant volume control method was proposed. The basic idea was according to the current system state and requirement the current controlled variable was selected and controlled as the target through the EEV opening regulation. A series of experiments were performed to testify all the conclusions above. The explanation on the unexpected experimental phenomenon was given in the end. This paper provided the theoretical guidance on the development of refrigerant system controller, and had its value on practical application.

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